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TECP 700-700
Materiel Test Procedure 2-2-702*
Aberdeen Proving Ground

19 January 1966

U. S. ARMY TEST AND EVALUATION COMMAND
COMMON ENGINEERING TEST PROCEDURE

# EFFECTS OF ALTITUDE ON AUTOMOTIVE ENGINES

## 1. OBJECTIVE

The objective of this MTP document is to determine power loss in automotive engines caused by changes in ambient air density.

## 2. BACKGROUND

Atmospheric pressures and air densities decrease inversely with altitude. It follows, then, that atmosphere-breathing internal combustion engines lose performance with increasing altitude because there is insufficient oxygen to supply combustion demands. Engines aspirated normally are the most sensitive to altitude changes, whereas super-charged 4-cycle and blower-scavenged 2-cycle engines may be unaffected by moderate changes in altitude, depending upon the excess air supplied by the combustion air system.

A change in altitude results in a change of ambient temperature and pressure, both of which normally decrease as altitude increases. The temperature reduction is approximately 3.4° per 1000 feet, and the pressure reduction is about 0.93 inch mercury per 1000 feet between sea level and 10,000 feet. (Actual pressure reduction is normally a logarithmic function of elevation). Even though decreased air temperature tends to increase air density, the reduction in pressure more than offsets the temperature effect, so that the net result is a decrease in ambient air density as altitude increases.

Appendix A discusses the considerations to be considered when altitude testing automotive engines.

## 3. REQUIRED EQUIPMENT

a. For all testing
   1. Thermometers to measure
      a) Ambient temperature
      b) Humidity
   2. Barometer
   3. Thermocouples and temperature indicating devices to measure:
      a) Cylinder head temperature
      b) Fuel temperature
   4. Traction dynamometer
   5. Engine tachometer
   6. Fuel flowmeter
   7. Engine air-flow intake

*Supersedes Ordnance Proof Manual 60-303

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b. For all laboratory tests
   1. Fuel tank
   2. Muffler
c. For all altitude chamber tests
   Altitude chamber (simulate sea level to 12000 ft. - 75°F, 29.92 inch mercury to 13.0°F, 19 inch of mercury)
d. For all simulated altitude chambers
   1. Intake surge tank
   2. Intake pressure control valve
   3. Exhaust surge tank
   4. Exhaust pressure control valve
   5. Air flow measurement instrumentation
   6. Exhauster
e. For all compression-ignition engines:
   1. Smoke meter
   2. Thermocouples and temperature indicating device for:
      a) Transfer pump temperature
      b) Exhaust temperature
   3. Pressure gage to measure transfer pump pressure
f. For field tests:
   Drive line torque meters, if required

## 4. REFERENCES

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F. Altitude Performance of Aircraft Engines Equipped with Gear-Driven Superchargers, R. F. Gagg and E. V. Farrer, SAE Transactions, Vol 29, 1934.
G. AR 705-15, Operation of Materiel Under Extreme Conditions of Environment, with change 1, 14 October 1963.
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J. Weather Bureau Pamphlet No. 235

## 5. SCOPE

### 5.1 SUMMARY

This MTP describes the method of comparing spark ignition and compression ignition motor performance against established specifications at designated altitudes (air density and temperature) under laboratory and field conditions.

5.2 LIMITATIONS

None

# 6. PROCEDURE

## 6.1 PREPARATION FOR TEST

a. The project engineer shall familiarize himself with the contents of Appendix A (Considerations relating to altitude testing of automotive engines).

b. Instrument all test items to measure the following:
   1. Cylinder head temperature
   2. Fuel temperature
   3. Brake horsepower
   4. Engine speed
   5. Fuel flow (consumption)

c. Determine and record the density of fuel used.

## 6.2 TEST CONDUCT

### 6.2.1 Laboratory Testing

6.2.1.1 Altitude Chamber Tests

6.2.1.1.1 Spark Ignition Engine Tests - These tests shall be performed by the following procedures:

a. Attach a muffler and fuel tank to the engine under test and instrumentation to measure the engine air intake flow.

b. Operate the engine at its rated speed and maximum load for the dry air temperature and pressure conditions indicated in Columns G and H of Table I.

c. Insure that the following are within specifications:
   1. Engine timing
   2. Governor setting
   3. Valve lash
   4. Carburetor adjustments

d. When the conditions of (b) and (c) at the 14 specified dry air temperature/pressure conditions of Table I, are established:
   1. Record the following data:
      a) Chamber dry bulb temperature
      b) Chamber wet bulb temperature
      c) Chamber barometric pressure
      d) Cylinder head temperature
      e) Fuel temperature
      f) Fuel flow meter reading
      g) Engine air intake flow reading
      h) Engine speed
      i) Engine output torque
   2. Determine the following:
      a) Fuel consumption
      b) Air density
      c) Engine horsepower

TABLE I

ALTITUDE TEST CONDITIONS AND REQUIRED PERFORMANCE

AUTOMOTIVE TYPE ENGINES

| A<br>Test No. | B<br>Altitude (feet) | C<br>Standard Pressure (in. HG) | D<br>Standard Temp (°F) | E<br>Normal Alt Pow (1) (%) | F<br>Normal Alt Pow (2) (%) | G<br>Mil Spec Press (in. HG) | H<br>Mil Spec Temp (%) | I<br>Req % Normal Alt Power (3) |
|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 29.92 | 60.0 | 100.0 | 100.0 | 29.92 | 60 | 100.0 |
| 2 | 0 | 29.92 | | | | 29.92 | 125 | |
| 3 | 1,000 | 28.86 | 55.4 | 96.8 | 97.0 | | | |
| 4 | 2,000 | 27.82 | 51.9 | 93.6 | 93.6 | 27.80 | 118 | 88.2 |
| 5 | 3,000 | 26.81 | 48.3 | 90.5 | 90.8 | | | |
| 6 | 4,000 | 25.84 | 44.7 | 87.5 | 87.8 | 25.80 | 110 | 82.4 |
| 7 | 5,000 | 24.89 | 41.2 | 84.6 | 84.8 | 24.90 | 107 | 80.0 |
| 8 | 6,000 | 23.98 | 37.6 | 81.7 | 81.9 | 24.00 | 103 | 77.2 |
| 9 | 7,000 | 23.09 | 34.0 | 78.9 | 79.2 | 23.10 | 100 | 74.4 |
| 10 | 8,000 | 22.22 | 30.5 | 76.2 | 76.5 | 22.20 | 96 | 71.5 |
| 11 | 9,000 | 21.38 | 26.9 | 73.5 | 73.8 | 21.40 | 93 | 69.4 |
| 12 | 10,000 | 20.58 | 23.3 | 70.8 | 71.3 | 20.60 | 89 | 67.1 |
| 13 | 11,000 | 19.79 | 19.8 | 68.3 | 68.8 | 19.80 | 86 | 64.6 |
| 14 | 12,000 | 19.03 | 16.2 | 65.8 | 66.4 | 19.00 | 82 | 62.3 |

(1) Percent of sea level, standard condition horsepower for four stroke cycle, normal aspiration, spark ignition engine using dry air. Pressure and temperature conditions are shown in columns C and D. Altitude power is expressed by the formula: $H_{palt} = H_{psl}$ (density ratio - 0.1)/(0.9) where density ratio is the ratio of air density at sea level, standard conditions.

(2) Percent of standard condition power computed with correction factor contained in MIL-E-13929(Ord) and based on temperatures and pressures listed in columns C and D. This information is included to show correlation of MIL-E-13929(Ord) correction factor with above equation.

(3) Minimum acceptable altitude performance for spark ignition and compression ignition engines under specification conditions of temperature and pressure. Values shown are in percent of standard conditions brake horsepower as measured in Test 1 and are computed using correction factor and specification conditions.

d) Engine air consumption

e. Operate the engine under the dry air temperature/pressure conditions (Columns G and H of Tests 1, 7, 11 and 14 of Table 1 at the test engines specified cruise conditions (part-load and part-throttle):

1. Record the following:
   a) Chamber temperature
   b) Chamber barometric pressure
   c) Fuel flow meter reading
   d) Engine air intake flow reading
   e) Engine output torque
2. Determine the following:
   a) Fuel consumption
   b) Engine air consumption
   c) Air density
   d) Engine horsepower

6.2.1.1.2 Compression Ignition Engine Tests - These tests shall be performed by the following procedures:

a. Attach a muffler and fuel tank to the test engine, and a smoke meter to the muffler, and instrumentation to measure the engine air intake flow.

b. Operate the engine at its rated speed and maximum load for the dry air temperature and pressure conditions specified in Columns G and H of Table I.

c. Insure that the governor setting is within specifications.

d. When conditions of (b) and (c), at the 14 specified temperature/pressure combinations of Table I are established:

1. Record the following:
   a) Data indicated in Paragraph 6.2.1.1.1, d.1
   b) Smoke-meter reading
   c) Transfer pump pressure
   d) Transfer pump temperature
   e) Exhaust temperature
2. Determine the following:
   a) Requirements of paragraph 6.2.1.1.1 d.2
   b) Smoke limited power

e. Operate the engine under the dry air temperature/pressure conditions (Columns G and H) of Tests 1, 7, 11 and 14 of Table I at rated speed and 50, 60, 70, 80, and 90 percent of maximum load:

1. Record the following at the indicated loads:
   a) Percent of maximum load
   b) Data indicated in paragraph 6.2.1.1. d.1
   c) Smoke-meter reading
2. Determine the following at the indicated loads:
   a) Requirements of paragraph 6.2.1.1 d.2
   b) Smoke limited power

6.2.1.2 Simulated Altitude Chamber Tests:

6.2.1.2.1 Spark Ignition Engine Tests - These tests shall be performed by the following procedures:

a. Prepare the test facility as indicated in Figure I less than smoke-meter.

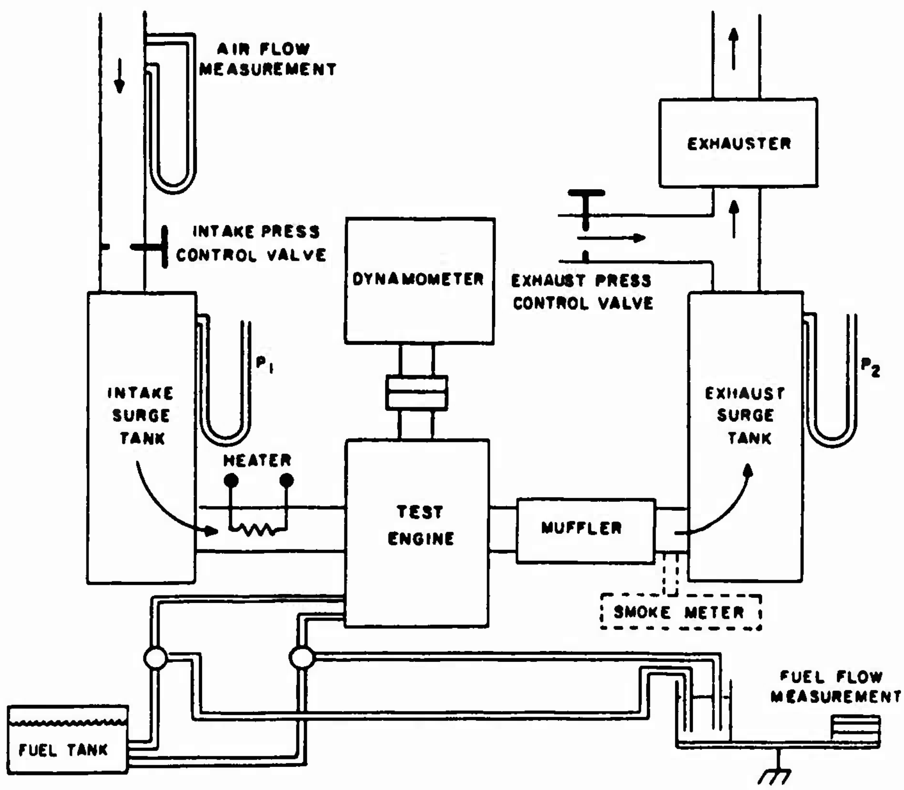


FIGURE I. SCHEMATIC DIAGRAM OF A SIMULATED ALTITUDE CHAMBER

b. Operate the engine at its rated speed and maximum load, under steady state conditions, for the dry air temperature and pressure conditions, indicated in Columns G and H of Table I.

c. Insure that the following are within specifications:

1. Engine timing
2. Governor setting
3. Valve lash
4. Carburetor adjustments

d. When the conditions of (b) and (c), at the 14 specified dry air temperature/pressure conditions of Table I are established:

1. Record the following data:
   a) Engine air intake dry bulb temperature
   b) Engine air intake wet bulb temperature
   c) Intake surge tank pressure (P1)
   d) Engine air intake air flow reading
   e) Cylinder head temperature
   f) Fuel flow meter reading
   g) Engine speed
   h) Engine output torque
   i) Exhaust surge tank pressure (P2)

   NOTE: P1 (air intake pressure) and P2 (exhaust pressure) shall be held to the same values to simulate the test atmospheric pressure conditions.

2. Determine the following:
   a) Fuel consumption
   b) Air density (engine intake)
   c) Engine horsepower
   d) Engine air consumption

e. Operate the engine under the dry air temperature/pressure conditions (Columns G and H of Tests 1, 7, 11, and 14 of Table at the test engines specified cruise conditions (part-load and part-throttle):

1. Record the following:
   a) Engine air intake dry bulb temperature
   b) Engine air intake wet bulb temperature
   c) Intake surge tank pressure (P1)
   d) Exhaust surge tank pressure (P2)
   e) Fuel flow meter reading
   f) Engine air intake flow reading
   g) Engine output torque
2. Determine the following:
   a) Fuel consumption
   b) Engine air consumption
   c) Air density (engine intake)
   d) Engine horsepower

6.2.1.2.2 Compression Ignition Engine Tests - These tests shall be performed by the following procedures:

a. Prepare the test facility indicated in Figure 1, including the smoke-meter.

b. Operate the engine to its rated speed at maximum load under steady state conditions, for the dry air temperature and pressure conditions specified in columns G and H of Table I.

c. Insure that the governor setting is within specifications.

d. When conditions of (b) and (c), at the 14 specified temperature/pressure conditions of Table I are established:

1. Record the following:
   a) Data indicated in paragraph 6.2.1.2.1 d.1
   b) Smoke-meter reading
   c) Transfer pump pressure
   d) Transfer pump temperature
   e) Exhaust surge tank temperature

   NOTE: A pressure difference between P1 and P2 of 1 inch of mercury will change the brake mean effective pressure approximately 0.67 pounds per square inch for 4-cycle engines, higher for 2-cycle engines.

2. Determine the following:
   a) Requirements of paragraph 6.2.1.2.1 d.2
   b) Smoke limited power

e. Operate the engine under the dry air temperature/pressure conditions (columns G and H) of Tests 1, 7, 11 and 14 of Table I at rated speed and 50, 60, 70, 80, and 90 percent of maximum load.

1. Record the following at the indicated loads:
   a) Percent of maximum load
   b) Data indicated in Paragraph 6.2.1.2 d.1
   c) Smoke meter reading
2. Determine the following at the indicated loads:
   a) Requirements of paragraph 6.2.1.2 d.2
   b) Smoke limited power

6.2.2 Field Tests

a. Mount the test engine in the test vehicle.

NOTE: Since the instrumentation for measuring engine torque is difficult and expensive to install, field testing shall be conducted in conjunction with MTP 2-2-806 to avoid unnecessary duplication of complex instrumentation installations.

b. Set up instrumentation to measure the engine air intake flow.

NOTE: Should it not be possible to run the field test in conjunction with MTP 2-2-806, the following additional instrumentation shall be required:

1. A traction dynamometer to measure load.
2. Drive line torque meters, to measure transmission inputs, providing the transmission efficiency is known for the speed and gear ranges at which the altitude test shall be conducted.

c. All torque and atmospheric measurements shall be made at rated engine speed, maximum power and stabilized conditions.

6.2.2.1 Spark Ignition Engine Tests

a. Operate the engine at its rated speed and maximum load at sea level (60°F and 29.92 inches of mercury dry air pressure).
b. Insure that the following are within specifications:
1. Engine timing
2. Governor setting
3. Valve lash
4. Carburetor adjustment
c. When the conditions of (a) and (b) are stabilized:
1. Record the following:
a) Altitude above sea level
b) Ambient dry bulb temperature
c) Ambient wet bulb temperature
d) Ambient barometric pressure
e) Cylinder head temperature
f) Fuel temperature
g) Fuel flow meter reading
h) Engine air-intake flow reading
i) Engine speed
j) Engine output torque
2. Determine the following:
a) Fuel consumption
b) Air density
c) Engine horsepower
d) Engine air consumption
d. Repeat (a) and (b) for altitudes of 5000 and 10,000 feet, under the dry air temperature/pressure condition of column G and H of Tests 7 and 12 of Table I.

NOTE: Field tests shall be conducted when atmospheric conditions are as near specifications as obtainable.

6.2.2.2 Compression Ignition Engine Tests

a. Attach a smoke meter to the engine muffler.
b. Operate the engine at its rated speed and maximum load at sea level (60°F and 29.92 inches of mercury dry air pressure).
c. Insure that the governor setting is within specifications.
d. When the conditions of (b) and (c) are stabilized:
1. Record the following:
a) Data indicated in Paragraph 6.2.2.1 C.1
b) The smoke meter reading
2. Determine the following:
a) Requirements of Paragraph 6.2.2.1 C.2
b) Smoke limited power
e. Repeat (b), (c) and (d) for altitudes of 5000 and 10,000 feet, under the dry air temperature/pressure conditions of columns G and H of Tests 7 and 12 of Table 1.

NOTE: Field tests shall be conducted when atmospheric conditions are as near specifications as obtainable, but simulation of specification conditions by restricting or heating the inducted air shall not be attempted. The engine must breathe and exhaust in the same ambient pressure for results to correlate and for observations of altitude induced

deficiencies to have significance.

6.3 TEST DATA

6.3.1 Preparation For Test

Fuel density in pounds per cubic feet.

6.3.2 Spark Ignition Engine Laboratory Tests

6.3.2.1 Altitude Chamber and Simulated Altitude Chamber Tests

a. Record the following:
1. Percent of rated engine speed
2. Percent of maximum rated load
3. Engine air intake dry bulb temperature, in °F
4. Engine air intake wet bulb temperature, in °F
5. Engine air intake barometric pressure, in inches of mercury (P1 for simulated).
6. Cylinder head temperature, in °F
7. Fuel temperature, in °F
8. Fuel flow, in gallons per minute
9. Engine air intake flow, in feet per minute
10. Engine speed, in revolutions per minute (RPM)
11. Engine output, in foot-pounds

b. Determine the following:
1. Fuel consumption, in pounds per minute
2. Air density, in pounds per cubic foot
3. Engine air consumption, in pounds per minute
4. Engine brake horsepower

6.3.2.2 Simulated Altitude Chamber Tests

Record the exhaust surge tank pressure (P2) in inches of mercury.

6.3.3 Compression Ignition Engine Laboratory Tests

6.3.3.1 Altitude Chamber and Simulated Altitude Chamber Tests

a. Record the following:
1. Percent of rated maximum load
2. Engine air intake dry bulb temperature, in °F
3. Engine air intake wet bulb temperature, in °F
4. Engine air intake barometric pressure, in inches of mercury (P1 for simulated)
5. Cylinder head temperature, in °F
6. Fuel temperature, in °F
7. Fuel flow, in gallons per minute
8. Engine air intake flow, in feet per minute
9. Engine speed, in revolutions per minute (RPM)
10. Engine output, in foot-pounds
11. Smoke-meter reading
12. Transfer pump pressure
13. Transfer pump temperature

14. Engine exhaust temperature
6. Determine the following:
   1. Fuel consumption, in pounds per minute
   2. Air density, in pounds per cubic foot
   3. Engine air consumption, in pounds per minute
   4. Engine brake horsepower
   5. Grade 3 smoke limited power, in horsepower

6.3.3.2 Simulated Altitude Chamber Tests

Record the exhaust surge tank pressure (P2), in inches of mercury

6.3.4 <u>Field Tests</u>

6.3.4.1 Spark Ignition Engine Tests

a. Record the following:
   1. Altitude above sea level, in feet
   2. Ambient dry bulb temperature, in °F
   3. Ambient wet bulb temperature, in °F
   4. Ambient barometric pressure, in inches of mercury
   5. Cylinder head temperature, in °F
   6. Fuel temperature, in °F
   7. Fuel flow, in gallons per minute
   8. Engine air intake flow, in feet per minute
   9. Engine speed, in revolutions per minute
   10. Engine output, in foot-pounds
b. Determine the following:
   1. Fuel consumption, in pounds per minute
   2. Air density, in pounds per cubic foot
   3. Engine air consumption, in pounds per minute
   4. Engine brake horsepower

6.3.4.2 Compression Ignition Engine Tests

a. Record the following:
   1. Altitude above sea level, in feet
   2. Ambient dry bulb temperature, in °F
   3. Ambient wet bulb temperature, in °F
   4. Ambient barometric pressure, in inches of mercury
   5. Cylinder head temperature, in °F
   6. Fuel temperature, in °F
   7. Fuel flow, in gallons per minute
   8. Engine air intake flow, in feet per minute
   9. Engine speed, in revolutions per minute
   10. Engine output, in foot-pounds
   11. Smoke-meter reading
   12. Transfer pump pressure
   13. Transfer pump temperature
   14. Engine exhaust temperature
b. Determine the following:
   1. Fuel consumption, in pounds per minute
   2. Air density, in pounds per cubic foot
   3. Engine air consumption, in pounds per minute

4. Engine brake horsepower
5. Grade 3 smoke limited power in horsepower

## 6.4 DATA REDUCTION AND PRESENTATION

The most important performance curve obtained from laboratory tests consists of dry air density on the x-axis versus observed brake horsepower on the y-axis. This curve shall lie above a plot of the horsepower listed in Column I of Table I. The observed brake horsepower curve indicates satisfactory or unsatisfactory engine performance to 12,000 feet for specified conditions. Depending on the altitude characteristics of the test engine, other curves such as brake specific fuel consumption, exhaust temperature, and air-fuel ratio shall also be plotted as a function of dry air density to indicate performance trends and to evaluate test results. As shown in Figure 2, specification altitudes corresponding to air densities may be added to extend the meaning of the performance curves.

In field tests, the engine power at sea level (standard conditions) is compared to the observed altitude horsepower. The sea-level horsepower, if obtained under atmospheric conditions differing from standard, must be corrected by means of equation (4). Partial pressure of atmospheric water vapor shall be read directly from tables such as those contained in Weather Bureau Pamphlet No. 235 when wet and dry bulb temperatures and barometric pressures are known. If these or similar tables are not available, then the partial pressure may be computed for equation (3) in which the saturation pressure, $P_w$, at the wet bulb temperature is taken from steam tables. The correction factor for actual test conditions is applied to the observed sea level power. If test conditions indicated in Table I are not obtained during test at altitude, the power should be corrected to specified conditions. To have satisfactory altitude performance, military vehicles must deliver at least 67 percent of maximum horsepower at 10,000 feet. (See Table I).

When significant variations in engine performance are encountered in laboratory testing (for example, specific fuel consumption or blow-by), these should be included in performance curves and analyzed fully with regard to altitude (expressed as air density). However, a complete analysis based on available altitude power must include considerations of air-fuel ratio as well as density. Figure 2 is included to illustrate the trend of diesel engine performance as a function of altitude effects. The upper set of curves is obtained from the part load data of Tests 1, 7, 11, and 14 and the maximum power runs of Tests 1 through 14. These curves present power as a function of air-fuel ratio for maximum as well as smoke-limited power. The second set of curves, power versus density (or corresponding specification altitudes), is obtained by cross plotting. The required performance from Column I of Table I is also shown. The smoke-limited as well as the maximum power air-fuel ratio line should lie about the required performance curve to comply with MIL-E-13929 (Ord) requirements.

Analysis of the performance curves may provide a means of predicting altitude performance analytically from basic, sea-level performance of power and specific fuel consumption. Operation below the smoke limit indicates complete combustion. When combustion is complete, power is proportional to the fuel rate. Also, if the air fuel ratio lines of Figure 2 are extended, they

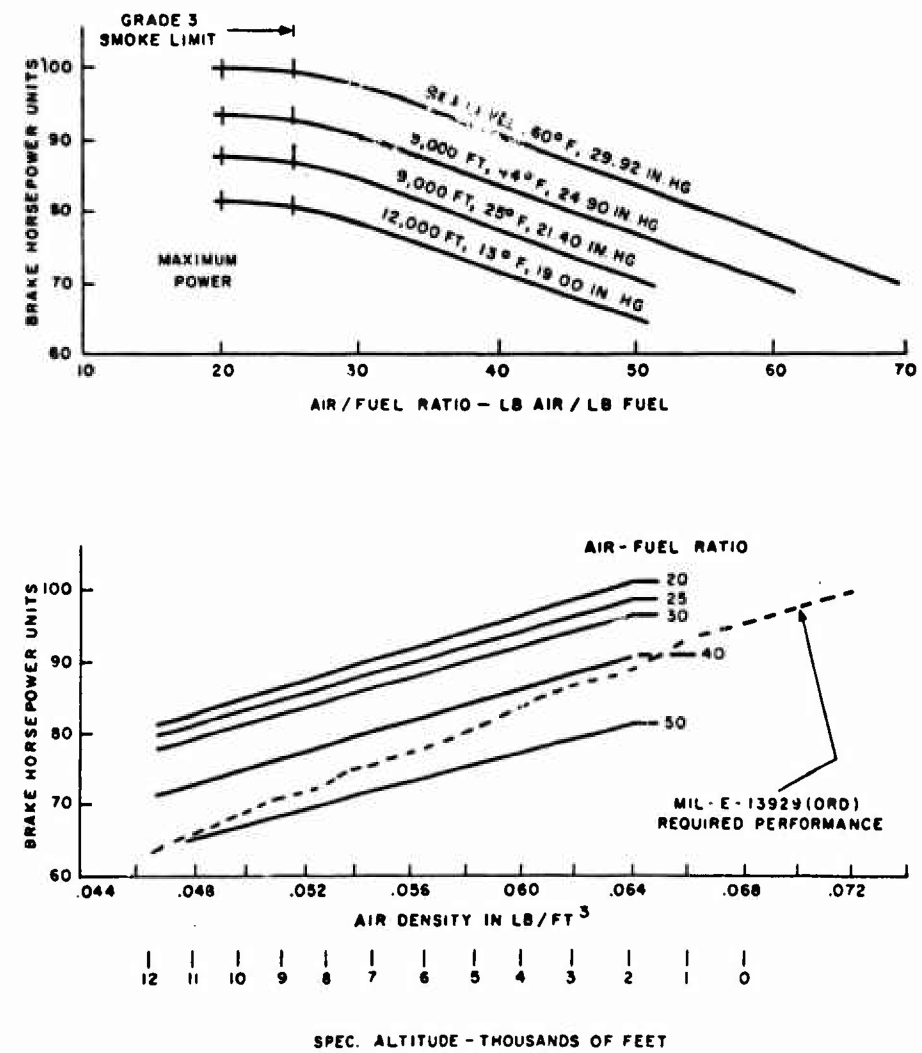


FIGURE 2 CURVES SHOWING POWER AS A FUNCTION OF AIR-FUEL RATIO (UPPER) AND AIR DENSITY (LOWER)

will converge on the y-axis at a negative horsepower which is equivalent to the rated speed friction horsepower. Based on these facts, the smoke-limited power for any altitude as a function of air density and fuel rate may be expressed by the general equation: $HP = AF - BF^2/d - C$ where "A" and "B" are constants and "C" is the friction horsepower, also considered constant at rated speed. "F" is the fuel flow rate in pounds per hour and "d" is the ambient air density in pounds per cubic foot. The constants may be computed by simultaneous solution of three equations at corresponding air densities and fuel ratios. For a 500-horsepower diesel engine, approximate values of the constants for rated speed are: A = 3.0, B = 0.00075, and C = 150.

With regard to analysis of field test results, sea-level performance, which is used as a reference to determine acceptable altitude performance, must be corrected to standard conditions when the test temperatures and pressures of Test 1, Table I, are not obtainable. To correct this performance, use equation (4) and disregard "$P_v$", humidity. As indicated in Table I, observed power for military vehicles should be 67 percent of the corrected value at 10,000 feet. Comparison of altitude and standard condition power is sufficient for drawing conclusions of satisfactory or unsatisfactory altitude performance based on MIL-E-13929(Ord) specifications, but all altitude-induced discrepancies, such as unbalance in injector nozzles, excessive knocking, and smoking, should be explained as fully as possible if encountered during field testing.

The following equations are applicable to this MTP:

(1) $$OHP = \frac{2\pi TN}{33{,}000}$$

(2) $$CF = \frac{(29.92)\,(Tc)}{(B-P_v)\,(520)}$$

(3) $$P_v = P_w - 0.000367B\,\frac{(t_w + 1539)}{(1571)}$$

(4) $$CHP = (CF)\,(OHP)$$

where B = Total Barometric Pressure in inches mercury with all temperature, elevation, and latitude corrections applied.
CF = Correction Factor for referring observed engine power to sea level standard conditions.
CHP = Corrected Engine Horsepower at sea level standard conditions with dry air inducted.
t = Wet Bulb Depression in °F, $t_d - t_w$
OHP = Observed Horsepower as determined with measured values of engine torque and speed.
$P_v$ = Partial Pressure of atmospheric water vapor in inches mercury absolute
$P_w$ = Saturation Pressure of atmospheric water vapor in inches mercury absolute at the wet bulb temperature
N = Engine Speed in Revolutions Per Minute
T = Engine Torque in Foot-Pounds
T = Intake Air Temperature in °F, 460 + °F
$t_d$ = Dry Bulb Temperature in °F
$t_w$ = Wet Bulb Temperature in °F

## GLOSSARY OF TERMS

The following terms apply to both compression and spark-ignition engines:

a. Air Density - Throughout this pamphlet, the term "air density" refers to pounds of dry air per cubic foot which actually is the specific weight. Although not technically correct, specific weight of air and air density are used interchangeably and have the same meaning in most altitude discussions.

b. Rated Speed - Rated speed is the highest number of revolutions per minute at which engines can be operated continuously. The exact value may be found in detailed specifications. When not listed in engine specifications, rated speed may be considered the same as governed speed.

c. Maximum Power - As used herein, maximum power is the maximum brake horsepower at rated speed with all engine accessories mounted and operating.

d. Rated Power - The rated power is the continuous brake horsepower at rated speed. In tests of experimental diesel engines in which detailed specifications are not available to establish this term, rated power may be taken as 80 percent of maximum power or power at governed speed recommended by the designer.

e. Full Rack - For diesel engines, full rack has the same meaning as full throttle in spark-ignition engines. At full rack, the helix on the injection plunger allows maximum fuel per cycle to be injected into the cylinder. Maximum power under normal conditions will therefore be obtained at full rack.

f. Satisfactory Exhaust Smoke - To be satisfactory, exhaust smoke of military diesel engines must be grade 3 or better, where grade 1 corresponds to clear; grade 2, haze; grade 3, light gray; grade 4, medium gray; and grade 5, dark gray. Smoke meters may be used to determine the exhaust smoke grade, but visual observations are acceptable.

APPENDIX A

CONSIDERATIONS RELATING TO ALTITUDE TESTING AND AUTOMOTIVE ENGINES

1. TYPES OF TESTING

In order to determine the effect of altitude on military engines and vehicles, two types of tests are conducted, laboratory tests and field tests. Laboratory tests are concerned with engine performance from sea level to 12,000 feet, while the field tests are used to determine the ability of vehicles to operate satisfactorily to an altitude of 10,000 feet (reference 4G) under specific conditions of temperature and pressure. Selection of test type is dependent entirely on desired information. Laboratory tests provide altitude engineering data on engines, whereas field tests are indicative of actual vehicle performance under climatic and vehicle-induced environmental stresses. Both laboratory and field tests are primarily dependent on accurate measurement of brake horsepower and ambient air density.

As shown in Table I, specification temperatures and pressures are in excess of those normally encountered at operating altitude, and these conditions cannot reasonably be expected during altitude field tests. Consequently, laboratory altitude tests should be conducted prior to field testing to determine performance under specified conditions of temperature and pressure for altitudes up to 12,000 feet and to evaluate factors, such as change in air-fuel ratio, that cannot be measured in field tests.

The objective of field tests is to measure engine power of military vehicles up to 10,000 feet and to compare this power to the minimum acceptable for satisfactory performance. Although the performance baseline is firmly established, power corrections by means of the MIL-E-13929(Ord) (reference 4H) correction factor have to be made when specification temperatures and pressures are not encountered. Secondary objectives of field tests include evaluation of factors such as engine starting and exhaust smoke at altitude.

2. EFFECTS OF ALTITUDE ON SPARK-IGNITION ENGINES

Spark-ignition engines are designed to operate at a relatively constant air-fuel ratio at open throttle and governed speed; as the altitude is increased, the air-fuel ratio will remain relatively constant because of partial fuel flow compensation in the carburetor or injector system. However, maximum power is limited by the maximum weight of air that can be inducted and, since inducted air weight is dependent on ambient air density, the open-throttle power will diminish as altitude increases. As stated, compensation is partial, and the air-fuel ratio is actually decreased until at 12,000 feet, the mixture will be approximately 25 percent rich. Although this excess fuel cannot be utilized in power output, it is effective in improving cooling and in lowering the octane requirement. (NOTE: Altitude-compensated carburetors hold the air-fuel ratio constant, but maximum power loss occurs in the same manner as described). Humidity must also be considered when testing spark-ignition engines, as an additional reduction in power is created by water vapor displacement of oxygen in the inducted air and by the adverse effect water vapor creates in the combustion process.

Altitude power loss characteristics differ in various engine designs;

hence, the need for altitude tests. The problem is not new, and considerable effort has been expended by the Army and other agencies, particularly aircraft engine designers, in evaluating its severity. The sequence of events occurring at altitude, as well as the extent of power loss, is well defined in applicable technical literature, and several altitude formulas are available which attempt to express rationally the effect of altitude on engine power. Based on one of these formulas, the loss in brake horsepower of a normally aspirated engine for standard altitude temperatures and pressures is shown in Column E of Table I. (For adaptation of this formula to gear-driven supercharged engines, see reference 4F). The average loss is about 2.0 percent per 1000 feet. Power loss, as computed with the correction factor (Equation (2)) contained in MIL-E-13929(Ord), is shown in Column F. Although these equations differ, they indicate very nearly the same power loss for corresponding temperatures and pressure conditions. Required performance of automotive engines, based on the MIL-E-13929(Ord) equation for specification temperatures and pressures, is shown in Column I for altitudes to 12,000 feet; however, the required field performance at 10,000 feet is not based on this formula, since the minimum acceptable performance at this altitude is specifically stated.

3. EFFECTS OF ALTITUDE ON COMPRESSION-IGNITION ENGINES

Altitude performance characteristics of compression-ignition engines differ from those of spark-ignition engines. In contrast to spark-ignition engines which operate at a relatively constant air-fuel ratio, compression-ignition engines operate over a wide range of ratios, the highest ratio occuring at idle speed and the lowest at full rack. (NOTE: Automotive diesels are often designed on the 2-stroke, blower-scavenged principle. In addition it its scavenging function, the blower may also act as a supercharger, in which case such engines may be relatively insensitive to altitude changes below 5,000 feet). During part-load operation, the air-fuel mixture will be very lean. Depending on rating, excess air may also be present at full rack; therefore, compression-ignition engines that are rated close to masimum power will have the highest sensitivity to altitude changes. For example, consider a compression-ignition engine that is running at rated speed and full rack at sea level. If the vehicle in which this engine is mounted is moved to progressively higher altitudes, the governor will hold the speed constant, and, since the fuel flow is fixed by the injection system which continues to operate at the same speed, the weight of fuel per unit time reaching the cylinders will remain unchanged. However, the weight of air inducted per unit time is dependent on the ambient air density, and, since the density decreases with altitude, the air-fuel ratio decreases. Depending on the engine rating and fuel characteristics, the power may remain constant until the air-fuel ratio falls to approximately 25 to 1. At this ratio, further increases in altitude will result in excessive exhaust smoke, but power will not necessarily diminish. (Maximum power is usually obtained at about 18 or 20 to 1). For this reason, it is necessary to obtain the maximum power that the engine will deliver regardless of smoke, as well as the maximum power with acceptable smoke conditions. Also, in performing and reporting compression-ignition altitude performance, air-fuel ratio as well as density and smoke limits must be considered as controlling variables. The effect of humidity on compression-ignition performance is small and, unlike the spark-ignition engine procedure, this atmospheric variable may be disregarded.

The required performance and test conditions for automotive diesels

are the same as those for spark-ignition engines, Table I. As stated, required performance is based on the MIL-E-13929(Ord) correction factor, but this equation is not entirely accurate when applied to diesels. Rational expressions of diesel altitude power are based on air-fuel ratios, fuel rates, and/or ambient air density, whereas the MIL-E-13929(Ord) correction factor is limited to temperature and pressure factors. An equation for expressing the smoke-limited power of a 4-cycle, normally-aspirated diesel is discussed in paragraph 6.4.

Laboratory tests are conducted on diesels as indicated in Figure 1 to obtain engineering data. Field tests of vehicles with diesel engines follow the same general procedure as previously described in that sea-level performance is determined and compared to altitude performance under specification conditions. Basic instrumentation is practically identical to that previously described and must be adequate for determining air flow, fuel flow, brake horsepower, and atmospheric conditions.